ENGLACIAL DRIFT.[1]

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Introduction.

Among the unsolved problems of glacial geology none, perhaps, are more important or pressing at the present time than the relative abundance and significance of the englacial drift. Although this subject has received its due share of attention in the recent literature of the science, the views of the leading glacialists are still strongly contrasted. Thus Chamberlin and others hold that the englacial drift was exceedingly scanty in amount, consisting chiefly of a few far-traveled, angular, and unglaciated bowlders now scattered over the surface of the drift; while Upham, the foremost exponent of the opposing theory, finds in the englacial drift the chief source of all the manifold forms of modified drift and also of drumlins.

The arguments of those who minimize the englacial drift are based chiefly upon the local character of the drift, the supposed paucity of englacial drift in modern glaciers, and the mechanical difficulty of accounting for a differential upward movement in the ice-sheet whereby large volumes of basal drift or ground moraine became englacial. The cogency of these arguments is beyond question; and a careful study of the recent literature satisfies me that, as the case now stands, the *onus probandi* may fairly be said to rest upon those who regard the englacial drift as an important factor in Pleistocene geology. Still, the englacial drift accounts so satisfactorily for far-traveled erratics, and the derivation from it of the modified drift is, theoretically, so relatively direct and simple, that faith in its sufficiency cannot be lightly relinquished.

In his recent paper on the "Discrimination of Glacial Accumulation and Invasion,"[2] Upham has, it seems to me, made a substantial

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[2] Bull. Geol. Soc. of America, 6, 343–352.

contribution to the general theory of the Pleistocene ice-sheet; and my chief purpose now is to analyze this idea that the ice-sheet was, over a considerable part of the glaciated area, formed *in situ* by snow accumulation, trace it to its logical conclusions, and show that it also throws important light upon the more special problem of the englacial drift.

Probable Early History of the Pleistocene Ice-sheet.

In this discussion a sharp distinction may properly be made between mountainous tracts, like the Adirondacks, Green Mountains, and White Mountains, and the plain or peneplain surface characteristic of the greater part of the glaciated area. The first-named topographic type, although the more exceptional, may conveniently be considered first.

In mountainous districts, or where the relief features are so strongly accentuated as to cause appreciable climatic differentiation, the general refrigeration of the climate, due chiefly, it is probable, to a marked elevation of the northern part of the continent, led first to the development of glaciers of the Alpine type in the higher valleys. These descended, under the influence of gravity, below the climatic zone in which they originated; as the level at which terminal ablation balanced the downward movement was gradually lowered, they became confluent; and finally, emerging from the mountains, they deployed upon the plain country, forming relatively sluggish or stagnant piedmont glaciers. But the extension of the piedmont glaciers by simple invasion cannot continue indefinitely, for the reason that with progressive refrigeration the annual snowfall finally exceeds the annual melting over the plain country as well as the mountains; at first near the margins of the piedmont glaciers only, but gradually extending farther and farther from them.

This cumulative snowfall, which mantled alike hills and valleys, and changed slowly through *névé* to glacial ice, must have tended in some measure to check or arrest the motion of the ice which had flowed outward from the mountains. Owing, however, to the forward motion of the piedmont glaciers, as well as to their termination on tracts where a short time before ablation had been in excess of snowfall, they must have terminated somewhat abruptly or with high marginal gradients;

and the conditions were, therefore, extremely favorable for their over-riding the new and still stationary ice-fields by which they were invested, in the manner indicated by the experiments of Favre, Bailey Willis, and others, on the compression and folding of sedimentary deposits of unequal thickness or rigidity.[1] The overridden tract or zone of ice must slowly acquire the motion of the overriding sheet, and thus in its turn come to override other tracts. In fact, it seems to me very probable that this process of overriding and absorption would continue almost indefinitely, extending, possibly, over a large part of the glaciated area. The only alternative views are that the piedmont glaciers became stationary, or that they were able by simple thrust to induce motion in the embryo and still sedentary ice-sheet across a breadth of hundreds of miles. The theory of overriding lies between these extremes.

Assuming a uniform annual snowfall over the area of the sedentary ice-sheet, it is obvious that since its area is gradually extended southward by the progressive climatic refrigeration, while the annual ablation as gradually diminishes northward, its thickness must increase backward from the margin. To the surface gradient thus resulting must be added the southward gradient of the surface of the land, which was probably augmented by differential continental uplift.

If, as Upham holds,[2] and as certainly seems most probable, the precipitation of snow over the growing ice-sheet was not uniform, but greatest for the first one hundred to two hundred miles inward from the margin, the surface gradient must have culminated on these peripheral tracts, diminishing gradually backward. This condition would, obviously, favor an early beginning of outward movement or flow in the marginal zone, and tend in an equal degree to retard motion in the central area.

It seems a reasonable assumption that the period of the growth and culmination of the ice-sheet, equally with that of its waning and disappearance, must have witnessed marked climatic oscillations of long period. In fact, we would hardly be justified in supposing that the great crustal movement which gave us the Ice Age was steadily progressive, without interruption or reversal, until its final culmination.

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[1] See, also, Upham's paper on "Drumlins and Marginal Moraines of Ice-sheets," Bull. Geol. Soc. of America, 7, 22.

[2] Bull. Geol. Soc. of America, 6, 344.

During each period of climatic amelioration and increased ablation of the sedentary ice-sheet its margin must have retreated to the northward; and since the ablation must have rapidly diminished northward, snowfall exceeding ablation within a few miles of the margin, we have here another efficient cause of a high marginal gradient; that is, precipitation and ablation coöperate to accentuate the frontal slope of the ice-sheet. Now, the chief factors in determining movement of the ice-sheet were, undoubtedly, its thickness and marginal gradient. We have few reliable data derived from observations on modern ice-sheets to indicate the magnitude which these factors must attain to inaugurate movement in an ice-sheet formed *in situ* over such a dissected peneplain as is presented by the surface of a large part of Canada and the northern United States, many of the valleys having contrary or transverse directions. But the absence from a large part of the glaciated area of mountains or dominant heights of land requires us to assume that over considerable tracts the sedentary ice-sheet did eventually begin to flow without having experienced the overriding or shearing thrust of the piedmont ice-fields. The outward movement thus originating in the peripheral tracts during a period of excessive ablation must have extended backward, perhaps until it met the forward thrust of the piedmont glaciers.

During a period of active growth of a sedentary ice-sheet each annual snowfall advances its margin, and increases its thickness by amounts depending upon the distance from the margin. Although the zone of maximum precipitation does not necessarily coincide exactly with that of most rapid growth or maximum excess of precipitation over ablation, we may assume that they would not be widely separated, and that the locus of most rapid growth would, therefore, be found at a moderate distance, say one hundred to two hundred miles from the margin. If we could only know the normal ratio of vertical to horizontal or areal growth, we might, assuming that climatic oscillations began at an early period of its history, reach a definite conclusion as to the probable extent of the ice-sheet when it first began to move or flow outward. We may, however, attack the problem in another way. The equivalent of one foot of ice is, perhaps, not too large an estimate of the average annual excess of precipitation over ablation on the zone of maximum growth. Warm periods may arrest and reverse the areal growth while the central tracts continue to increase in thickness, though possibly at a diminished rate, thus

accentuating the frontal slope; that is, while cold periods must mean, on a plain country, relatively rapid horizontal growth and therefore a growth unfavorable to early movement, the ice-sheet becoming proportionally thinner, a moderately warm period following a cold one means continued growth in thickness with a great reduction of area and hence a growth especially favorable to early movement, the ice-sheet becoming proportionally thicker. It seems probable, therefore, that a warm period following a cold period of two or three thousand years duration would induce movement in the sedentary ice-sheet, and that movement at this early period might affect almost simultaneously the peripheral and central tracts.

Assuming now that movement of the ice-sheet was inaugurated during a warm period, and that the southern margin of the ice has retreated far to the north through ablation, developing a bold and aggressive front, it is obvious that the succeeding cold period must have caused a rapid extension of sedentary ice southward from the front of the moving sheet, and the former would inevitably be progressively overridden and absorbed by the latter. It may be noted, also, that these phenomena would be repeated with each recurring climatic cycle. This section may be summarized as follows:

The Pleistocene ice-sheet was formed *in situ*, by snow accumulation, over the main part of the plain country within the glaciated area. The motion which this sedentary ice-sheet subsequently acquired probably originated in several ways.

1. In the vicinity of the mountainous tracts, through its being progressively overridden and absorbed by piedmont glaciers.

2. At a distance from mountains and independently of piedmont glaciers, by the steepening of the marginal gradient, chiefly through increased ablation due to climatic amelioration.

3. The cold period following each period of marked climatic amelioration and consequent recession of the margin of the ice-sheet must have spread a new sedentary ice-sheet over the deglaciated area, which would be progressively overridden and absorbed by the re-advance of the older sheet.

Basal Relations of a Sedentary Ice-sheet.

During the slow accumulation of the ice-sheet, and before it began to move, the ground beneath it, which must have been saturated with water, was probably frozen solid to a considerable depth, possibly

nearly if not quite to the bottom of the residuary soil or other surface detritus; that is, down to the firm rocks. There could have been no original plane of separation or movement between this frozen soil and the overlying ice-sheet, for the ice did not merely rest *on the detritus*, but extended down through it to the lower limit of frost. This point will probably be conceded by all who have noted the tenacity with which ice in winter adheres to the ground, pavements, etc., when the temperature is below freezing.

Ice, in the thin sheets with which we are familiar, separates readily from the underlying soil in mild weather, while the subsoil still remains frozen, for the simple reason that the solar heat passing downward through the ice is arrested by the surface of the ground, causing a local rise of temperature along the contact between the ice and frozen soil. The operation of this principle evidently depends upon the thermal diaphaneity of the ice, and hence it does not in general admit of application in the case of snow, which is relatively opaque to both light and heat. Therefore, this cause of separation cannot be invoked in the case of the growing ice-sheet of the Glacial Period, since it was a necessary condition of its formation that the winter snows remained unmelted upon its surface, accumulating thus to a great thickness and slowly changing downward through *névé* to glacial ice. We must suppose, then, that from the top of the ice-sheet to the lower limit of frost in the soil was one solid mass — ice above and ice and soil below.

It may safely be assumed that over the glaciated area in preglacial times, as now in lower latitudes, the superficial detritus or soil was chiefly the residuary product of quiet chemical decay. This is equivalent to saying that it consisted chiefly of clay and sand. Hard, angular fragments of rock, such as are so common in the till, were wanting, and the rounded, bowlder-like nuclei of decomposition must have been of rather rare occurrence at points near the surface of the ground or above the lower limit of the frost.

If we may assume a thickness of residuary detritus commensurate with that which now mantles the Southern States, it is, perhaps, probable that over considerable areas solidification by freezing would fail to reach the firm, undecomposed rocks beneath. However that may be, it is certain that with increased thickness the ice-sheet became a more and more efficient protection to the ground against the climate of the Ice Age, and the steady efflux of heat from the earth's interior would

thus tend to gradually loosen the hold of the frost upon the rocky substratum.

Observations in the arctic regions and at high altitudes show that the ground may become frozen to a depth of several hundred feet, and R. S. Woodward's theoretical discussion[1] of the subject not only corroborates these observations, but indicates that the downward penetration of the frost may be comparatively rapid. Thus if the mean annual temperature of the surface should fall from 60° F. to 10° F., the ground would become frozen to a depth of 400 feet in less than one thousand years. Russell suggests[2] that the great depth of frozen soil reported at Yakutsk, Siberia (382 feet), and at other arctic stations, may be due in part to the surface accumulation of ice through the growth of the tundra, and that possibly the rate of diffusivity of temperature assumed by Woodward is too high, but he does not seriously question the main conclusion with regard to the efficiency of frost penetration.

It is well known that glaciated areas are not in general those of most extreme cold. A humid climate is the first essential; and, given that, a temperature low enough throughout the year to insure precipitation chiefly in the form of snow and to prevent excessive waste by summer melting — a mean annual temperature a few degrees only below freezing, like that on the Mount St. Elias coast of Alaska — is all that is required for active glaciation. In harmony with this conclusion, we find that the extremely frigid areas, such as the interior of Alaska and northern Siberia, are relatively dry and non-glaciated. For this reason, and also because the increasing thickness of a sedentary ice-sheet would tend to neutralize the downward penetration of frost, we need not suppose that the ground beneath the ice would be frozen to any great depth or far below the detrital layer.

The relatively high conductivity and diffusivity of pure ice, in comparison with the covering of *névé* and snow, would tend, through the steady efflux of the terrestrial heat, to raise the temperature of the lower portion of the ice-sheet to the melting point. On the other hand, the high latent heat of fusion would tend to prevent extensive melting of the ice until the entire basal portion of the sheet had attained approximately the melting temperature. The effect of the

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[1] Bull. Geol. Soc. of America, 1, 130–132.

[2] Ibid.

weight of the ice itself in lowering the temperature of fusion of its base would be too small to require consideration here.

The interesting question now arises as to the most probable plane of shearing when the sedentary ice-sheet finally begins to move. We may assume that the initial basal shearing or gliding plane will be approximately the same whether the ice-sheet begins to move in obedience to its own weight or through the overriding thrust of a thicker northern sheet. In any case, or whatever the cause of movement, it is, as we have seen, most likely to be inaugurated during a period of climatic amelioration. Above the bed-rock, three layers of material require consideration: (1) The ice-sheet proper; (2) the frozen soil beneath it, to which it is still firmly united; (3) the unfrozen soil resting upon or passing downward into the solid rocks. Under the assumed conditions of climatic amelioration and a basal rise of temperature in the ice-sheet, we may suppose that the frozen soil, in consequence of its lower position and the relatively low specific heat of earthy and stony substances, would tend to rise in temperature and to thaw earlier than the pure ice. Hence the frozen soil may, perhaps, be regarded as weaker and more susceptible of shearing than the clear ice, although at temperatures well below freezing the reverse relation would probably hold true. We thus arrive at the conclusion that at the inception of movement in any part of the ice-sheet the ice is possibly stronger than, but essentially continuous with, the frozen soil, and the latter is clearly stronger than the unfrozen soil; and hence it would follow that the most probable initial plane of slipping or shearing would be in the unfrozen soil, the frozen soil and overlying ice moving *en masse*, and the movement being lubricated by the unfrozen soil, which would be at most points of an argillaceous and plastic character. Although a residuary soil naturally becomes firmer and more rock-like downward, and is, therefore, weakest near the surface, we should not lose sight of the fact that, since frost causes a notable expansion of the soil, a recession of the lower limit of the frost toward the surface, through the efflux of the terrestrial heat and consequent rising of the isogeotherms, would tend to leave at the lower surface of the frozen soil a thawed-out layer of loose and yielding texture.

Observations heretofore made on modern glaciers and ice-sheets are of little value in this connection, because nowhere in the field of observation are realized the conditions that must obtain at the base

of a sedentary or recently sedentary ice-sheet. The true glaciers or ice rivers of Alpine districts, Greenland, etc., are mere lobes of ice descending under the influence of gravity from the edges of *névé* fields and ice-caps into a climatic zone where permanent ice cannot form; and hence they are moving over unfrozen soil, and the ice is wasting by melting on its under as well as its upper surfaces. The great *desideratum* is, evidently, a shaft or boring in the interior of Greenland extending through the entire thickness of the ice-sheet and a hundred feet into its rocky bed. This would expose the true basal relations, thermal and otherwise.

In his recent paper on the "Influence of Débris on the Flow of Glaciers,"[1] Professor Russell assumes that ice is analogous to pitch in that its plasticity or tendency to flow is diminished by inclosed *débris*. This assumption is undoubtedly safe for temperatures well below freezing. But if it is a sound principle that when the temperature of the ice is rising and near the melting point the inclosed rock *débris* will, on account of its lower specific heat, tend to rise in temperature faster than the ice and thus to loosen by melting the bonds between it and the ice, then the comparison with *débris* in pitch would seem to hold good only in the improbable case when the imbedded stones caused a local softening of the pitch. The *débris* in ice would not lead to extensive melting, on account of the high latent heat of melting ice. But if the temperature of the *débris* rises ever so little above 0° C. (32° F.), it ceases to be a source of strength in the ice, the effective section of the ice being diminished in proportion to the amount of *débris*. This view seems to be abundantly confirmed by Professor Chamberlin's Greenland studies, for he has given us no more striking and significant fact than the relative facility with which the ice shears along innumerable lines of *débris;* and the evidence is conclusive that the ice, to a large extent, slides over the inclosed *débris*, instead of dragging it along, as it would if the *débris* were firmly frozen into the ice. Granting, however, that the frozen soil would be more rigid and indifferent to gravitative stresses than the clear ice above it, the fact remains that the unfrozen soil at the base is more yielding and plastic than either; and hence, although we may reasonably conceive definite shearing planes as distributed through a considerable thickness of the ice-sheet, the lowest plane, and the true base of the ice-sheet, will still be at the lower limit of frost.

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[1] Journal of Geology, 3, 823–832.

So far as I can learn, everywhere within the range of observation modern glaciers are either sliding over their ground moraines or they rest directly upon the firm bed-rock, just as many rivers, at ordinary seasons, flow quietly over deep beds of gravel and stones or over bare ledges. In both cases active erosion of the bed-rock floor is nearly at a standstill, for where it is not protected by the stagnant *débris* the ice or water are not well suppled with stones, without which they can do little. In the case of the river, periods of flood or of greater fall or volume in the past must be postulated to set the detritus in motion and account for the effective erosion of their channels. Similarly for the glacier, the entire ground moraine must be set in motion. Increased thickness and velocity of the ice would probably tend to accomplish this. But to my mind rectilinear striæ, often scores of feet in length, are an impossibility unless we conceive the entire mass of the ground moraine as inclosed in the moving ice.

Professor Chamberlin's observations in Greenland show that any number of horizontal shearing planes may be postulated, with a corresponding reduction of the basal velocity; but I see, with Upham, no escape from the conclusion that during the period of active and efficient glaciation of the bed-rock surfaces the ground moraine was very scanty or wholly wanting, being incorporated with the moving ice. Imagine a modern glacier or ice-sheet as launched upon a plain covered by 25 to 50 feet of sedentary detritus passing gradually downward into firm rocks, and consider how little chance there would be for the development on the underlying bed-rock of a typical glaciated surface so long as the ice and soil are essentially distinct. The preliminary removal of the detritus by simple thrust and drag is seen not to be a valid explanation when we consider the great breadth of the glaciated area and the enormous marginal accumulation which would inevitably result. A true ground moraine between bed-rock and ice, and distinct from both, belongs to the waning stage of the ice-sheet and to lobes of ice (glaciers) descending from an ice-cap or *névé* field into a climatic zone where permanent ice cannot form.

All this appears to be quite consistent with the local origin of the greater part of the till or ground moraine of the Pleistocene ice-sheet and the well-established fact that the total movement of the ice amounted to hundreds of miles if we simply suppose that through the granular plasticity of the ice, or a series of shear planes, the basal, drift-laden layer moves much more slowly than the overlying clear ice.

Absorption of Drift by the Pleistocene Ice-sheet.

Glacialists are sharply divided in opinion as to the power of an ice-sheet to absorb or incorporate with its mass the detritus over which it moves, and the arguments *pro* and *con* have been stated with much fullness and force in recent papers by Upham, Chamberlin, and others.[1] It is clearly incumbent upon the advocate of the englacial theory to prove that large volumes of drift may become englacial. It seems to me that this has not been satisfactorily done as yet, and, as previously stated, the chief purpose of this paper is, if possible, to reinforce the englacial theory at this point.

The sedentary ice-sheet, as we have seen, holds in its grasp a large part of the surface detritus; and if, as I believe, the initial shearing plane is normally or usually at the lower limit of frost, a considerable body of detritus, mostly of a fine or impalpable character (preglacial residuary soil, etc.), is englacial from the beginning of movement of the ice-sheet. When a sedentary ice-sheet is overridden by a piedmont glacier, and still more when a sedentary ice-sheet is overridden by the re-advance of an earlier ice-sheet, the conditions must be favorable for the transfer of drift from the base of the earlier sheet to a somewhat elevated position in the composite sheet which results from the overriding. We may suppose that the overriding sheet will carry with it not only its own englacial drift, but will drag along, also, a part of its ground moraine or subglacial drift. This complex process will be repeated with each marked recession and re-advance of the ice-sheet.

It is altogether probable that each important recession of the ice-sheet, and not alone the final recession, was characterized by numerous glacial rivers and lakes and an extensive development of modified drift in the well-known forms of kames, eskers, deltas with abrupt northern margins, etc. It is obvious that such eminently loose and porous deposits would be completely permeated by and form an essential part of the succeeding sedentary ice-sheet. Thus material which may have slowly become englacial through the movement of an earlier ice-sheet is englacial from the beginning of the succeeding sheet; or, if the later ice should move over these deposits, their forms and structures are very favorable to their being absorbed by the ice through shearing and flexing.

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[1] Upham has recently cited all the more important of the later contributions to this discussion. Bull. Geol. Soc. Amer., **5**, 72, 73.

Some of the illustrations accompanying Professor Chamberlin's valuable description of the Greenland glaciers[1] are well calculated to dispel any doubts that may exist in the minds of geologists as to the power of a glacier to absorb detritus by shearing and flexing movements. The flexures are certainly very remarkable, considering that, strictly speaking, ice is neither viscous nor plastic. Chamberlin's explanation of movement as the result of granulation and a continuous adjustment of the granular structure to gravitative stresses through differential melting and regelation obviates in a measure the difficulty of accounting for the complex movements observed; but the fact remains that relatively slight obstructions, whether of solid rock or uncompacted drift, are sufficient to originate sharp overthrust flexures and obliquely ascending shear planes, which are marked by prominent bands of *débris*—ground moraine in process of absorption by the ice. To Chamberlin belongs the credit of observing and depicting more clearly, perhaps, than any previous writer the mechanism of the transfer of drift from a subglacial to an englacial position. There can be no doubt now that in a lee the ice, at least under certain conditions, will drag, in consequence of basal friction, sufficiently to give rise to a sharp flexure or a thrust fault between it and the ice which passes over the obstruction. A part of the latter is being constantly curved downward and backward and added to the stagnant ice, and thus the thickness of the latter increases with the distance from the lee slope, and the axial plane of the flexure rises to higher levels in the ice; or, if the conditions of granulation, velocity, etc., determine shearing as well as or instead of flexing, the shearing plane will likewise tend to rise in the ice.

In an earlier publication[2] Professor Chamberlin has analyzed glacial motion and shown the importance, in a detailed study, of distinguishing vertical pressure, due to the thickness and weight of the ice, and flowage pressure, due to its horizontal movement. The former culminates in the basal central and the latter, as a rule, in the superficial peripheral tracts. These two pressures coöperate on stoss slopes, and hence glacial erosion reaches its maximum intensity there. Glacial striæ record, almost exclusively, the movements of the ice-sheet in its final stages, and it is well understood that the general absence of

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[1] Journal of Geology, **3**, 478, Figs. 28–30, Bull. Geol. Soc. Amer., **6**, 203–214, plates 5–9.

[2] Seventh Ann. Report, U. S. Geol. Surv., 186–192.

striæ on lee slopes above a certain low angle of declivity means that the flowage pressure then so far predominated over the vertical pressure that the ice tended to arch over the lee slope instead of flowing down it. Under the greater vertical pressure and lower velocity of the central areas the ice will hug the lee slopes more closely, and they will be more generally glaciated. In this case, however, as truly as in the first, the ice in the lee must drag—that is, move more slowly than the ice above it; and this retardation will almost inevitably, according to Chamberlin's Greenland observations, lead to flexing or shearing and the absorption of detritus. We are thus brought to the conclusion that from the summit or crest of nearly every elevation with an abrupt lee slope a stream of detritus flowed onward and upward into the Pleistocene ice-sheet during its progress over the land. And it is obvious that, if this view be even measurably sound, the mechanism is provided for the abundant transfer of drift from a subglacial to an englacial position. This important conclusion may be presented in another way. The detritus urged up or worn from the stoss slopes by the movement of the ice clearly did not descend the lee slopes under the pressure of the ice, else these slopes would not be unglaciated; therefore it must have passed on into the ice, or else have accumulated in a passive form on the lee slopes. It was probably disposed of in both these ways, but it is well known that stoss slopes are quite as likely as lee slopes to be encumbered by ground moraine.

The recently published experiments in ice motion made with wax by E. C. Case[1] have a special interest in this connection. They tally very closely with Chamberlin's Greenland observations, and materially strengthen our general conclusion that the forward motion of the ice over an uneven topography gives rise to obliquely ascending currents and that from the summits of elevations basal detritus is carried, not down the lee slopes, but forward and upward into the body of the ice.

It must, however, be conceded by the englacialist that during the period of maximum glaciation for any area, when the ice was thickest and the vertical pressure had its maximum value, a large proportion of the drift reaching the top of stoss slopes probably remained in the bottom of the ice and was dragged down the lee slopes and away from the elevations without losing its subglacial position. This must have involved the striation and polishing of the lee slopes, and the condi-

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[1] Journal of Geology, 3, 918–934.

tions were unfavorable for the detachment of blocks of rock — the rending and quarrying operations of the ice-sheet. Later, when the vertical pressure was less and the velocity of flow greater, the ice hugged the lee slopes less closely, and the conditions became favorable for the detachment of blocks by the ice moving under the combined vertical and flowage pressure across the crests of the elevations. If the ice actually pulled away from the lee slopes to an appreciable extent, or even tended to do so, the local relief of pressure may, perhaps, have led to the freezing on these slopes of subglacial water. This sedentary ice, penetrating the joint cracks of the rocks and by its expansive power starting the joint blocks from their positions, and later, by its continued growth, becoming continuous with the moving ice, may have assisted in plucking away blocks and fragments of rock from the lower as well as the upper portions of the lee slopes, thus tending to maintain the high angle of declivity so characteristic of lee slopes.

The broken and precipitous character of typical lee slopes is, to my mind, rather inconsistent with the passage down them, during the detachment and removal of the blocks, of much ground moraine; and this conclusion is in harmony with the facts that they are not now, as a rule, banked high with till and that we often find a surface train of angular blocks leading away from them. That the blocks thus borne away from a lee slope were, in many cases, carried in the ice instead of being dragged along beneath it is proved by the occurrence of entirely angular and unglaciated forms and the fact that, as in the case of the great Madison bowlder in New Hampshire, the original orientation of the blocks is sometimes unchanged.[1]

In the preceding paragraph I have but followed in the footsteps of Professor Chamberlin, for he has shown[2] very fully and clearly that the ice flowing over and around prominent ledges and rocky hills will naturally carry away in true englacial fashion many angular blocks and more or less of other forms of detritus, and also that this, as he supposes, scanty englacial drift is now distinguishable from the ground moraine on which it rests. Having granted this much, Professor Chamberlin is, apparently, obliged to ground his argument for the essential scantiness of the englacial drift upon the assumption,

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[1] Appalachia, 6, 66.

[2] Journal of Geology, 1, 47–60 and 255–267.

nowhere explicitly stated, that but little drift was dragged or carried by the ice up the stoss slopes and over the crests of the ledges and hills, for this material would obviously have an equal or better chance than that worn from these elevations of becoming truly englacial. But the validity of this tacit assumption cannot be admitted. The severe glaciation of the stoss slopes is against it; and, aside from this consideration, it is difficult to understand how, except in valleys trending with the glacial movement, any considerable amount of detritus that was transported or dragged a good fraction of a mile or more from its source could help crossing one or more elevations. Certainly its course would need to be very devious to avoid them.

Again, Professor Chamberlin[1] has given us the important principle that, during the closing stages of the Ice Age at least, the surface of the ice-sheet must have been depressed over highlands and elevated over valleys, and that, movement being determined by surface gradient alone, the ice would flow toward rather than from the highlands. This principle would thus operate to increase the ground moraine on the hilly tracts at the expense of that in the valleys and lowlands; and it has occurred to me that perhaps we have here an explanation of the long, ridgelike accumulations of till which often, on the plain country, border or separate the north-south valleys. Just as a river does not make its chief deposits in the deepest part of its channel, where the current is strongest, but along the margin, building up the flood plain, so the ice stream tends to crowd the detritus out of north-south valleys from the line of swiftest to the lines of slowest motion. From these till ridges we pass easily and naturally to drumlins. Every glacialist knows that the drumloid slopes of till, which may, in my opinion, be regarded as embryo drumlins, although most characteristic of stoss slopes, occur abundantly on lee slopes also. They seem to indicate an attempt on the part of the ice-sheet to carry or drag a large amount of drift up the stoss slopes. When the drift gains the crest it is in part carried away into the body of the ice by the freer motion of the ice above this level, tending to leave the lee slopes bare, as already noted. But during the waning of the ice-sheet its movement over the rock hills and ledges finally became so feeble that it could no longer urge all the subglacial drift, the amount of which was probably being augmented by basal melting, up the stoss

[1] Seventh Ann. Report U. S. Geol. Surv., 184, 185.

slopes, and it began to accumulate upon them. Each increment was so thoroughly compacted and pressed down by the ice, aided by the natural tenacity of the clay, that the effective stoss slope was gradually raised until the accumulation of till finally overtopped the rocky obstruction and became a drumlin. This view seems to be in entire accord with Professor Chamberlin's recent suggestion with regard to the origin of drumlins.[1]

Perhaps the general conclusions to which my studies have now led me may be best stated as follows: A large part, probably the main part, of the preglacial surface detritus was englacial in the sedentary ice-sheet and remained so after the ice began to flow during the entire period of the growth, culmination, and early decline of the ice-sheet, or while the hard bed-rock surface was being actively abraded and striated. During this time, which embraced the greater part of the Glacial Period, the preglacial detritus not originally incorporated in the ice and the material worn from the ledges by the ice itself became englacial, in large part at least, through overriding, shearing, and flexing movements of the ice, a hard surface of drift-shod ice in direct contact with the uneven bed-rock surface appearing to be essential to the rectilinear striation of the latter. During the later stages of the decline of the ice-sheet basal melting set free considerable volumes of the hitherto englacial drift to form the ground moraine; and just as the frontal or terminal moraine, also composed of material set free by the ablation of the ice, records the cessation of the forward movement or invasion of the ice-sheet, so the basal or ground moraine records the gradual cessation of the glacial abrasion of the bed-rocks. The relative suddenness of this change from active erosion to deposition in any area is indicated by the fact that, generally speaking, the ground moraine rests everywhere upon normally striated surfaces. In other words, as soon as the ground moraine began to appear through basal melting it was essentially motionless, for ice moving over a bed of detritus in a way to impart motion to it would inevitably give rise to sidewise, oblique, and devious movements of individual stones which would tend to obscure and efface the rectilinear striation of the bed-rock surface. The ground moraine as it accumulated was pressed down by the ice to form the typical hardpan. In part it accumulated on stoss slopes through obstruction to, and in part on lee slopes

[1] Journal of Geology, 3, 480.

through protection from, the forward movement of the ice, forming drumloid slopes and, later, drumlins.

It is not a necessary deduction from this view that the bed-rock always rises to a good height in drumlins, since the hardpan character of the ground moraine and the tendency of the ice at this stage to flow over loose materials, as observed by Niles, Spencer, Chamberlin, and many others, make of the initial knob or boss of the ground moraine an efficient gathering point for more material as fast as it is furnished by the melting of the ice. The main point may be presented in another way. When, as in the earlier and maximum stages of the ice-sheet, the basal temperature was below freezing, the freezing of subglacial waters made and kept the detritus a part of the ice-sheet; and when, as in the later stages of the ice-sheet, the basal temperature rose above freezing, the ice relaxed its hold on the detritus and flowed over it, as attested by observations on modern glaciers.

It is a necessary consequence or corollary of this view that transportation of drift by simple drag is relatively unimportant, if not impossible. The transportation is almost wholly englacial, as insisted by Upham,[1] but highly differential, being extremely slow in the basal layers and more and more rapid at higher levels. The detritus reaching the highest levels in the ice is carried farthest, not only because of the higher velocity, but also because it remains for a longer time in the ice.

The history of an ice-sheet embraces, as regards the basal temperature, two distinct and contrasted periods: (1) The period of growth and maximum development, when the temperature of the lower part of the ice is permanently below freezing; (2) the period of decline, when the basal temperature is above freezing. The first is the period of active abrasion and scoring of the bed-rock, all detritus being frozen into the ice as fast as formed. Furthermore, the water resulting from superficial summer melting of the ice, descending through crevasses to the basal portion of the sheet and refreezing there, not only adds the newly formed detritus to the base of the moving sheet, but also, perhaps, favors an actual downward growth of the ice-sheet, whereby detritus which has previously become englacial is raised to greater heights in the ice, the growth of the ice-sheet being chiefly upward by snowfall in winter and downward by basal freezing in summer.

[1] Bull. Geol. Soc. Amer., 6, 348.

During the second period the ice-sheet wastes by basal as well as superficial melting, the englacial drift becomes subglacial (ground moraine), and glacial erosion gradually ceases.

The prevailing opinion among geologists, as recently collated by Culver,[1] is evidently strongly against the efficiency of glacial erosion, and this trend of opinion is certainly justified so far as it is based upon observations on living glaciers. Observations on the velocity and abrasive power of modern ice-sheets have never been made. But the relatively high efficiency of the Pleistocene ice-sheet in this respect is clearly proved by the undisputed facts that over practically the entire glaciated area north of the terminal moraine *all* the preglacial sedentary soil and partially decayed rock were worn away, involving on a large aggregate area extensive erosion of the hard, unaltered rocks, and that the prevailing color of the ground moraine below the sharply defined limit of postglacial oxidation is that of crushed rock, and not of residuary or other preglacial detritus. The latter fact, which seems to have been but little regarded, is probably of equal significance with the first, and the general conclusion based upon both these is further sustained by observations upon the proportions of distinctively glacial detritus in the ground moraine.[2] It is a logical deduction from the view developed here that there can exist in the ground moraine, in general, no real or definite distinction between subglacial and englacial till, because, broadly speaking, it has all been englacial.

Probably no feature of the Greenland glaciers revealed to us by Chamberlin's studies will be regarded by glacialists with greater interest and astonishment than the beautiful stratification and lamination of the ice. He states, and his photographic illustrations show, that the stratification is most perfect in the lower, drift-laden portion of the ice, being only obscurely seen in the upper white ice. It is especially interesting to note in this connection that in the drift-laden ice the stratification is due chiefly to the mode of distribution of the drift or rock *débris*, which forms numerous relatively thin and continuous layers approximately parallel with the bottom of the glacier and often exhibiting flexures and faults where the ground over which the glacier moves is sufficiently uneven. Chamberlin refers all this englacial drift

[1] Trans. Wis. Acad. Sci., etc., 10, 339–366.

[2] Proc. Boston Society of Natural History, 25, 131–138.

to one source. It is ground moraine which has been absorbed by the ice through flexing and shearing movements, and it proves that this process of absorption is essentially continuous. The thinness and persistence of the layers of *débris* also prove that the planes of shearing extend forward indefinitely into the body of the ice, and do not tend to die out, as they would if the ice were a viscous or plastic substance. This differential movement along an inset layer of *débris* must drag it out and tend to give it persistence, even if the process of absorption in that plane is intermittent.

Furthermore, we find here a most striking confirmation of the conclusion previously stated, that, under certain conditions at least, the *débris* in the ice is an element of weakness and tends to give rise to shearing and gliding planes. This whole process of lamination by shearing is beautifully attested by the marked projection of the upper layers on the precipitous margin of the ice due to ablation. The under surfaces of the projecting layers are fluted by the fragments of rock lying in the plane of shearing. But in spite of this indication that the ice moves over the inclosed detritus, it is obvious that the movement must also drag it along; and when we consider how intimate this process of lamination shearing is, producing in extreme cases as many as twenty distinct layers in an inch, it can hardly be doubted that the englacial rock fragments, more especially if of small size, must suffer faceting and striation after the manner of the ground moraine. Thus one supposed distinction between subglacial and englacial drift in a measure disappears, and is no longer available as an argument to minimize the englacial drift of the Pleistocene ice-sheet.

Professor Chamberlin has noted[1] that while the Greenland glaciers commonly slide over the ground moraine in their lower courses, allowing it to accumulate beneath them, they appear in their upper courses to drag and carry it along, fitting snugly in their respective valleys and scoring the ledges over which they move. By parity of reasoning we may suppose that, although at its lower extremity the ice is observed to slide over the interstratified *débris*, farther back from the margin the *débris*, being frozen in the ice, is urged along and glaciated by the motion of the ice.

I have observed something analogous to this lamination shearing of

[1] Journal of Geology, 3, 67 and 208–210.

glacial ice in the obsidian flows of the Lipari Islands. In consequence, perhaps, of incipient crystallization, or of partial relief from pressure, due to the fact that the lava continued to flow after it had begun to stiffen, imprisoned or dissolved aqueous vapor is liberated along certain planes coincident with the plane of flowing, giving rise to layers of vesicles. These vesicular layers (analogous to *débris* layers in the glacier) become, with continued stiffening of the magma, relatively planes of weakness and hence shear planes — a true flowing movement which affects the entire body of magma being transformed in part, by continued pressure from behind, to mechanical shearing along definite planes.

Comparison with Modern Glaciers and Ice-sheets.

Perhaps the most cogent argument against the view that the drift of the Pleistocene ice-sheet was, during certain prolonged phases of its history, largely or chiefly englacial is that based upon the comparative rarity of englacial drift in modern glaciers and, seemingly, in modern ice-sheets. The general freedom of glaciers of the Alpine type from incorporated drift, other than that derived from lateral and medial moraines through the agency of crevasses, is, no doubt, attributable to the facts that their courses were long since swept relatively bare of detritus and that in their lower courses they are undergoing basal melting, and hence depositing rather than absorbing drift.

According to the observations of Chamberlin and Salisbury,[1] the numerous glaciers descending from the margin of the Greenland ice-cap present, in this respect, two types: (1) The drift-laden glaciers, which have commonly vertical sides and ends and predominate north of latitude 76°; (2) the apparently drift-free glaciers, which are commonly without prominent vertical sides or ends and predominate south of latitude 76°. Both these able observers state emphatically that in the drift-laden glaciers the drift is strictly a basal feature, rarely rising to greater heights in the ice than 100 to 150 feet even where the glacier may be a thousand feet or more in thickness. Furthermore, these observations are regarded as fully confirmed by those made upon the countless icebergs of the neighboring seas. We may, perhaps, reasonably suppose that the greater abruptness of the northern glaciers is due in some measure to the more rapid melting of the drift-

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[1] Journal of Geology, 3, 875-902.

laden basal layers of the ice, in consequence, as already explained, of the low specific heat of the imbedded *débris*, and that, possibly, the northern glaciers are more generally drift-laden because the severe climate tends to prevent basal melting. Certain it is that the englacial drift is, in general, most in evidence where the basal conditions most closely approximate those of an ice-sheet in its prime.

It appears to me, however, extremely improbable that all the englacial drift of the Greenland glaciers has been absorbed by the ice during its comparatively short and steep descent from the margin of the ice-cap. I would suggest instead that a considerable part of it represents the lower, drift-laden portion of the ice-cap itself. Whether these lobes of the ice-cap are well charged with drift or not is of no special significance in a study of the Pleistocene ice-sheet of North America, unless we can regard them as reliable indications in this respect of the constitution of the parent ice-cap. Assuming with Chamberlin that, while the upper, clear ice of the Greenland glaciers increases rapidly in thickness from the lower end upward toward the ice-cap, the basal, drift-laden ice increases but little if any in thickness, is it a necessary conclusion that in the ice-cap itself, thousands of feet in thickness, the englacial drift is limited to the lower 100 to 200 feet? To answer in the affirmative is to lose sight of the principle that the velocity of the ice increases rapidly upward from the bottom. The ice-cap virtually spills over the edge of the plateau through deep V-shaped notches; and to my mind the conclusion is unavoidable that a much larger proportion of the upper, clear, and relatively mobile ice will flow down than of the lower, drift-laden, and relatively immobile ice. It is probable that increased declivity would in any case accelerate the velocity of the upper more than of the lower layers of ice, but this contrast would certainly be greatly intensified by the section of the valley — broad and open above, and narrow below.

It is the general belief of geologists that if Greenland were divested of its ice-cap it would exhibit continental relief — elevated margins and a depressed interior. Hence we may assume that the ice-cap attains its maximum thickness in the central areas, and that a smothered mountain range separates this main body of ice from the overflow fringe of glaciers along the coast. The futility of regarding these smaller coastal glaciers as representative, in the matter of englacial drift, of the great ice-cap from the marginal and superficial portions of which they originate is obvious.

The Humboldt glacier and others of the great glaciers of the Greenland coast belong in quite a different category, occupying as they do, apparently, the lower courses and mouths of the great interior valleys; but, terminating in the sea, we can only judge of their basal conditions by the icebergs to which they give rise. It is, perhaps, fair to assume that, through basal melting, these giant glaciers, like their smaller brothers which fail to reach the sea, are building platforms of the ground moraine beneath their extremities and thus permanently shallowing or filling up the bays along the coast. But that the icebergs often carry away generous loads of drift is well known, and we may specially note in this connection (1) that perhaps many of what pass for small bergs are really large bergs deeply laden; (2) that bergs well ballasted with drift cannot possibly be overturned so as to expose the drift to observation; and (3) that the drift-bearing part of a berg, under the combined influence of the higher specific heat of rocky *débris* and gravitation, must melt away very rapidly when the temperature of the water is above freezing. Again, these giant glaciers are simply ice rivers draining at lower levels the great *mer de glace* or interior sea of ice; and, just as in the case of the water of a lake and its outlet stream, the velocity of the ice must be greatly accelerated in passing from the *mer de glace* to the glacier. From this premise the conclusion follows irresistibly, as previously noted, that the glacier will consist in much larger proportion than the *mer de glace* of the upper, drift-free ice. Hence we can hardly suppose that even a clearly exposed section of the Humboldt glacier would reveal to us a true and undistorted vertical section of the Greenland ice-cap, for the basal layers certainly would not be adequately represented. Thus observation is baffled at every point, unless, indeed, a boring should some time be made in the interior of Greenland. I see no reason, however, to doubt that the *mer de glace* is well supplied with englacial drift, or that wherever the ice is actively abrading its bed it holds in its mass the entire volume of detritus, moving, full armed and without any intervening shield or ground moraine, over the unprotected bed-rock.

That the englacial drift rises to a great proportional height in the Greenland or any other ice-cap appears to me, however, by no means a necessary conclusion. Probably very little rises to a greater height than 500 feet, or possibly 1,000 feet, even where the thickness of the ice is one to two miles. In fact, none of the suggested processes of

absorption seem competent to diffuse the detritus through any considerable thickness of the ice, or to carry it far above the summits of the obstructions which give rise to the shearing and flexing movements. I conceive it, rather, to be somewhat crowded in the slow-moving basal strata of ice, whence it is early set free by basal melting to form the ground moraine, and to thin out rapidly upward. Among the causes tending especially to check or limit the upward movement of drift in the ice is the progressive increase in the velocity of the ice from the base upward, in obedience to the principle, already noted, that a current tends to force floating bodies from the lines of highest velocity to those of lowest velocity.

It is possible, however, that, as virtually pointed out by Upham,[1] an important exception to this limitation of the range of englacial drift should be made for the case when a later sedentary ice-sheet is overridden by the re-advance of an earlier sheet, the height attained by the englacial drift depending then upon the thickness of the overridden sheet. Again, a mountainous tract lying in the pathway of the ice-sheet may lead to the incorporation of drift at exceptionally high levels. In fact, the Malaspina glacier is a capital example. According to Russell, the drift which mantles the outer margin of this great piedmont glacier covers, even in parts of the area where it is forest-clad, not less than a thousand feet in thickness of ice, and where it is not forest-clad it rises to still greater heights. Russell states that this superglacial drift consists wholly of the lateral and medial moraines of the tributary glaciers descending from the Mount St. Elias range.

"All of the glaciers which feed the great piedmont ice-sheet are above the snow line, and the *débris* they carry only appears at the surface after the ice descends to the region where the annual waste is in excess of the annual supply. The stones and dirt previously contained in the glacier are then concentrated at the surface, owing to the melting of the ice. This is the history of all the moraines on the glacier. They are formed of the *débris* brought out of the mountains by the tributary Alpine glaciers and concentrated at the surface by reason of the melting of the ice."

Probably this incorporation of drift at high levels would still occur, but on a grander scale, if the St. Elias range were completely buried in ice moving across it. Regarding these St. Elias glaciers as rivers

[1] Bull. Geol. Soc. Amer., 7, 21, 22.

of ice tributary to a sea of ice, the thought is naturally suggested that perhaps the drift-laden ice tends, on joining the piedmont glacier, to flow out across the ice sea regardless of its depth, and thus, while actually descending topographically, rise to greater heights in the ice-sheet. This principle would also, obviously, find application in the case of valleys or depressed areas of any form transverse to the general direction of flow of the ice-sheet, and it thus becomes simply a broader phase of the principle of the absorption of detritus by shearing and flexing. These considerations lead me to venture the opinion that, while depths of englacial drift amounting to 1,500 or 2,000 feet or more, or to one fourth to one third of the thickness of the ice-sheet at its maximum, as held by Upham, cannot be regarded as strictly normal or as prevailing over considerable areas of plain country, they are possible under the special conditions indicated.

Relations of Englacial Drift to Modified Drift.

The manifold forms of modified drift, or washed and stratified gravels, sands, and clays, of glacial origin, forming deltas, terraces, overwash or apron plains, eskers, kames, etc., although occurring almost wholly in valleys and on lowlands, constitute in the aggregate a considerable fraction of the total volume of the drift. Concerning the source of the modified drift, there is as yet no general agreement among glacialists. The main views, of which all others may be regarded as modifications, are (1) that the modified drift has resulted chiefly from the washing and assorting of the till or ground moraine by glacial streams during and following the waning and disappearance of the ice-sheet, (2) that it was derived from englacial drift through the agency of subglacial streams, and (3) that it had its origin in englacial drift which became superglacial by ablation and was washed and assorted by superglacial streams. Undoubtedly all of these theories are required to account for the totality of the modified drift, and the real question is as to their relative importance.

It is inconceivable that the ice-sheet could disappear without some washing or modification of the ground moraine. It is, however, a noteworthy fact that the till does not present about the heads of southward sloping valleys or elsewhere evidences of such extensive erosion as should be required for the general or unqualified accept-

ance of this view. The absence, as a rule, of strongly marked erosion lines in the ground moraine is particularly striking in the case of the drumlins, since their highly definite and characteristic contours due to glacial molding make them extremely delicate records of aqueous erosion. Every glacialist knows how rare and insignificant are the evidences of drumlin erosion which can be referred to subglacial streams. Superglacial and marginal streams have here and there notched the summits or terraced the sides of protruding drumlins, and frost and rain-wash doubtless accomplished some degradation of the drumlins after the disappearance of the ice and before the mat of vegetation was spread over them. But when all these modes of erosion are taken into account, the waste which drumlins have suffered still appears so trifling that, if they were regarded as representative in this respect of the ground moraine in general, all subglacial material might, perhaps, be safely neglected as a source of modified drift. In fact, the advocates of the derivation of the modified drift from the ground moraine should, it would seem, also espouse the theory that drumlins are mere erosion remnants of a sheet of till of much greater average thickness than that which now encumbers the glaciated area.

It may be noted, however, that, as I have elsewhere pointed out,[1] the ice-sheet was probably accompanied, at least in its later stages, by a more or less complete system of subglacial drainage; and during all the time while the ground moraine or subglacial till was accumulating through basal melting, and also while it was still englacial, through the agency of numberless shearing planes, it was undergoing modification by the washing out of its finer constituents, clay and rock flour. Obviously, of this differential erosion no distinct trace or scar could be expected to survive the disappearance of the ice-sheet, especially since the action could not have been sharply localized, but must have affected in some degree almost the entire area of the ground moraine.

While not denying or doubting that the ground moraine has made, in various ways, substantial contributions to the modified drift, I recognize that the relations of the still englacial drift to glacial drainage afford a more direct and satisfactory explanation of the main part of the modified drift.

The real problem appears, then, to be as to the relative efficiency of subglacial and superglacial streams. Upham, the foremost advocate

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[1] Proc. Boston Society of Natural History, 25, 117.

of the efficiency and sufficiency of superglacial streams, holds that the englacial drift became superglacial, by surface ablation of the ice, in sufficient volume to account for practically all the various types of modified drift, and that the superglacial streams were adequate for its transportation and deposition. That this must be the history of a part of the modified drift is obvious from the fact that these conditions are realized in modern ice-sheets, but they are only realized, it must be added, to a very limited extent.

It is a common and, perhaps, a fair assumption that in Greenland and Alaska are exhibited now, on a smaller scale, nearly all the essential phases of the disappearance of the Pleistocene ice-sheet. A general survey of these and other regions now undergoing glaciation has revealed only one notable occurrence of superglacial drift, namely, that mantling the outer margin of the Malaspina glacier; and that, as we have noted, is of somewhat exceptional origin, inasmuch as it is not derived from strictly normal englacial drift. Little more can be said for superglacial streams. They are either entirely wanting or they are short-lived, being almost invariably swallowed up by crevasses and rarely discharging over the margins of the ice-sheets. Nowhere, so far as I am aware, have superglacial streams been observed actively washing and distributing superglacial drift. Assuming, as I think we must, that the englacial drift is crowded in the basal layers of the ice, enormous wastage of the ice must occur before it becomes superglacial; and the extreme brittleness and consequent fissuring of the ice protect it from the ravages of superglacial streams, until in the course of time it becomes forest-clad and assumes the character of an ancient soil.

It seems to me very probable, however, that when considerable sections or areas of the Pleistocene ice-sheet were so far wasted as to be absolutely stagnant, and when superglacial drift covered its surface and checked the melting of the ice, the still existing crevasses may have become choked with drift to such an extent as to keep the streams superglacial or in channels open to the sky, and thus to realize the essential conditions of the formation of modified drift from superglacial drift. Meanwhile, however, or before these conditions are realized, the water resulting from the melting of thousands of feet of ice has escaped from the ice-sheet through subglacial channels, and during its entire subglacial course the main body of the englacial drift has been within its reach and undergoing modification. This consideration and

the contemplation of the deposits being made at the present time by the Fountain stream, the Yahtse, and other rivers emerging from the base of the Malaspina glacier, not to multiply examples, satisfy me that not only is the modified drift, so far as it is being formed at the present time, the product chiefly of subglacial streams acting on englacial drift, but that it probably was so in Pleistocene times. When it is generally recognized that the modified drift requires not one but several theories, criteria will, doubtless, be established by which we may determine for any normal example whether it has been derived chiefly from subglacial, englacial, or superglacial drift.

The Transportation Argument.

Notwithstanding the abundant and indubitable evidence that a small part of the drift of the Pleistocene ice-sheet is far-traveled, it is generally conceded that the great bulk of the drift is of relatively local origin, and good authorities hold that this is substantially true for the modified drift as well as till. My own studies in the Boston Basin have satisfied me, however, that the modified drift and till of this region are somewhat contrasted in this respect, though perhaps not more than we should expect, considering that the modified drift was transported by water as well as by ice. For example, with the aid of several students in the Massachusetts Institute of Technology, I examined the composition of a prominent esker on the northwest shore of Weymouth. North of this point in the line of glacial movement are three broad belts of rocks: First, slates and conglomerates of the Boston Basin (Carboniferous), about thirteen miles; second, hornblendic granites, diorite and felsite, with some Cambrian slate and quartzite, eight to ten miles; third, mica schists, muscovite granites and gneiss, pegmatite, etc., extending into New Hampshire. We found, on looking over some tons of material, that of all which was coarse enough for easy identification about 50 per cent. is from the first belt, 40 per cent. from the second, and 10 per cent. from the third. Subsequently, at points only two to five miles from the northern edge of the Boston Basin, I found the proportion of material from the first belt in the modified drift very small, 10 per cent or less. Hence it is probably safe to assume that more than half of the coarser material of the modified drift of the Boston Basin is five to ten miles from its source and a good fraction as much as twenty miles.

But conceding that the readily identifiable constituents of the drift,

whether modified or unmodified, are chiefly of distinctly local origin, it may still be doubted whether much weight should be attached to this fact as an argument against the view that practically the entire volume of the drift was englacial in the earlier and maximum stages of the ice-sheet. For the purpose of this discussion the drift may be divided into three parts: First, the preglacial detritus, which must have been chiefly of a residuary and clayey character and highly oxidized (red and yellow), like the residuary soils of the South; second, the finer products of glacial erosion, rock flour, etc., formed chiefly on stoss slopes and for the most part unoxidized; third, the coarser part of the drift, the identifiable rock fragments, which must be almost wholly of glacial origin and derived chiefly from the lee slopes.

The preglacial residuary and sedentary soil was probably partly swept away by aqueous erosion during the elevation of the continent and before the formation of the ice-sheet. What was left of it probably became incorporated with the ice-sheet in its earliest stage; and we may well suppose that during the various vicissitudes of the ice-sheet, and through the coöperation or alternation of glacial, lacustrine, and fluvial transportation, it has been carried in large part beyond the limits of the glaciated area. Certainly there is little indication of its presence in the composition of the drift; and experiment shows that an admixture of a very small proportion of highly oxidized residuary clay, like that of the South, with a typical till is readily detected in the change of color. It is a natural suggestion, therefore, that the Lafayette and Columbian formations of the South have been derived, along their northern borders, in part from the preglacial residuary soils of the North. The finely comminuted and unoxidized glacial detritus constitutes now the basis or matrix of the till, and is very largely represented in the modified drift. But except to a very limited extent it is entirely unidentifiable as to its source and the distance of its transportation. The vast deposits of modified drift in Southeastern New England, and the great average thickness of till in Ohio and other interior States, not to mention distinctly morainal accumulations, indicate, however, when compared with the scanty deposits of drift over many northern areas in New England and Canada, that a large volume of the older, finer, and less readily identifiable part of the drift is relatively far-traveled. In its earliest stages the ice-sheet, we may reasonably suppose, wore away and absorbed a considerable thickness of rotten rock underlying the residuary soil; and during its max-

imum stage, as already noted, the hard rocks suffered glacial abrasion on the lee slopes as well as on the stoss slopes. The conditions must then have been very unfavorable to the rending of the ledges and the detachment of fragments and bowlders; but this came later with the decline of the ice-sheet, when the flowage pressure so far predominated over the vertical pressure that the ice pulled away from instead of following down the lee slopes.

Approaching the subject in this way, I can see no escape from the conclusion that the rock fragments and bowlders must date chiefly from the later stages of the ice-sheet. Hence they must have been, in general, the last material to be absorbed by the ice-sheet and the first to be deposited by basal melting. Under favorable conditions of flexing or shearing a small part of this material attained a high level in the ice and enjoyed a long glacial transport; but the fact that most of it is still near the parent ledges will, I judge, be found quite consistent with the englacial theory if due allowance be made for the relatively short time that it was inclosed in the ice and for its basal position and the low velocity of the basal layers of the ice. Although the total forward movement of the ice, as indicated by far-traveled erratics, appears to have been as much as five or six hundred miles, and even in some parts of the glaciated areas perhaps a thousand miles, a basal slipping of one twentieth of that distance or less would probably be regarded as sufficient to account for the erosion of the bed-rock surface and the normal distribution of the identifiable fragments. In this connection I venture to repeat the suggestion that possibly the total movement of the ice has been overestimated, the more distant erratics having been, perhaps, transported in part by water, and not wholly by the ice-sheet, each marked recession of the ice-sheet providing a series of glacial lakes and rivers along its margin.

Since writing out this paper I have realized more distinctly than before that the points relating to the entire volume of the drift having been englacial during the active erosion of the bed-rock, the efficient protection afforded glaciated surfaces by even a thin layer of till, and the consequent ruling out of drag as a mode of glacial transportation have been previously stated by Mr. Upham.[1] But since I have approached the subject in quite a different way, and there are still minor points of difference, this general acknowledgment is, perhaps, preferable to any attempt at quotation.

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[1] Bull. Geol. Soc. Amer., 5, 71–86, etc.